Silica Aerogel Captures Cosmic Dust Intact

Peter Tsou
Jet Propulsion Laboratory, California Institute of Technology
Pasadena California 9110S-8099

The mesostructure of silica aerogel resembles strings of grapes, ranging in size from 10Å to 100Å. This fine mesostructure transmits nearly 90% of incident light in the visible, while providing sufficiently gentle dissipation of the kinetic energy of hypervelocity cosmic dust particles to permit their intact capture. Wc introduced silica aerogel in 1987 as a capture medium to take advantage of its low density, fine mesostructure and most importantly, its transparency, allowing optical location of captured micron sized particles. Without this feature., locating such captured particles in an opaque medium, e.g., polymer foams, is nearly impossible. The capture of hypervelocity particles has been extensively simulated in the laboratory. At the time of this symposium, more than 2.4 m^2 of 20 mg/ml silica aerogel will have been flown on Space Shuttle (STS-47, STS-57, STS-60, STS-64 and STS-68). This space demonstration of capturing hypervelocity particles ushers in a new, simple avenue to science in capturing intact cosmic dust from space. Since our introduction of aerogel for intact capture of cosmic dust, many useful features unique to aerogel have been identified. In the current era of a faster, cheaper and better political environment, it is obviously very advantageous to achieve great science by a simple and low-cost approach - to capture and return extraterrestrial samples passively in a flyby rather than robotically *or* by the landing of astronauts.

1. Introduction

Comets are spectacular solar system bodies. They appear to be well-preserved relics of the preplanetary material that accreted in the outer fringes of the solar nebula. These small and primitive cometary bodies are ice-rich and have been preserved by remaining deeply frozen in space. They have survived for most of the lifetime of the solar system by residing in the Oort cometary cloud some fifty thousand astronomical units from the Sun, The bulk of cosmic dust is likely to be either cometary or asteroidal in origin, with some even of interstellar origin and should constitute a unique repository of information concerning the formation and subsequent processing history of the condensed stellar nebula which became our solar system, Thus, the study of cosmic dust is important and may prove to be the rosetta to understanding the formation and subsequent processing of the solar system and possibly that of life, as well [1].

One of the major goals of planetary science is the detailed laboratory analysis of extraterrestrial samples [2], from a specific body with known history. Sample return from most extraterrestrial bodies is usually considered complex and costly and is only considered as a follow-on to a sequence of reconnaissance missions. It is possible, however, to collect cosmic dust left by a cometary coma or asteroid collisions and return it to Earth for detailed laboratory study. These types of space exploration missions can be done within a decade, at relatively low cost by highly simplified flyby missions.

However, planetary orbital motions dictate that cosmic particles approach spacecraft at relative speeds of the order of tens of km/s. It was not obvious at first that these hypervelocity particles could be captured intact without melting or vaporization. Worse yet, would be to have captured the cosmic dust but not be able to locate it in a capture medium. Unless the dust particles were captured in a transparent medium such as aerogel, they would be almost impossible to find, since these extraterrestrial dust of interest are extremely fine, ranging in size from 0.1 μm to 100 μm in diameter. A typical cosmic dust particle captured in the stratosphere is shown in Figure 1.

This paper traces our development of the intact capture technology that enables intact capture of cosmic dust at hypervelocities, a result that revolutionized the cosmic dust community [3]. Our second contribution to the dust community is the introduction of silica aerogel [4], which has been adopted as the new standard capture medium for cosmic dust collection. Results of actual space captures of hypervelocity particles are presented. Then, the unique features of silica aerogel, providing the rationale for this application of cosmic dust collection, are explored.

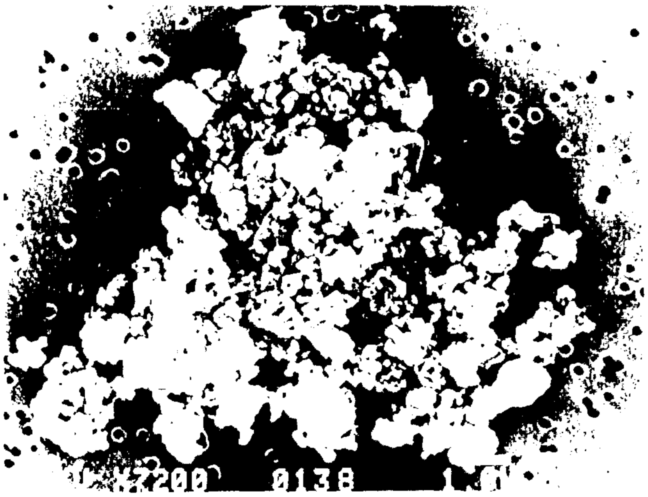

Figure 1. Stratospheric Cosmic Dust

2. intact Capture Technique

Extraterrestrial material has intrigued planetary scientists for a long time. Large chunks of meteorites have been displayed in museums and cut open for chemical, physical, isotopic and biogenic analyses. For small micrometeorite fragments, scientists have combed crater vicinities and ocean floors and melted tons of ice in search of extraterrestrial material. Only with the advent of space flights, did the capturing of particles in space begin.

For several decades, it was accepted that projectiles traveling faster than a speeding bullet could not be captured intact. It was believed that the only way to stop such hypervelocity particles, at speeds greater than 3 km/s and mostly in the range of tens of km/s, would be to convert the particle into plasma and collect the vaporized condensates, i.e., the atomization process, which is illustrated in Figure 2. This atomization approach would retain only the elemental composition of the particle. However, the collection of material from other planets by the atomization method would be not unlike an archaeologist first reducing an unearthed vase into atoms, and then trying to reconstruct the vase from the plasmatized atoms. One intact chip of the vase would be far more useful than a bottle of atoms of the entire vase. This realization instigated the search for a technique to capture hypervelocity extraterrestrial particles intact, preserving the structural phases and morphology of the particle [3], even if only for a portion of the particle. In so doing, intact capture would preserve the particle's structure and its full chemical and isotopic compositions as well.

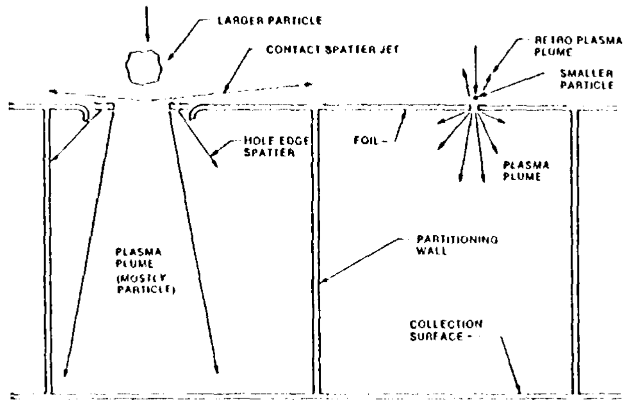

Figure 2. Atomized Capture

2.1 *Analytical Basis of Intact Capture*

Existing hypervelocity solid-into-solid impact theory was used to verify the theoretical possibility of capturing projectiles at hypervelocities without melting them. A test model of aluminum projectile capturing in popular styrofoams was used. Fortunately, the parameters needed to construct Hugoniot equations of state for aluminum, polystyrene, and foams of polystyrene for several densities were available [5]. Thus, using a graphic method with the equation-of-state parameters, the initial shock-pressure level at the interface of an aluminum projectile impacting solid aluminum (2.79 g/rid), solid polystyrene (1 .046 g/ml), and styrofoams of three densities (286, 55, and 16 mg/ml) as a function of the projectile's impacting speed has been calculated [6] and is shown in Figure 3.

For an aluminum projectile impacting solid polystyrene, melting would be initiated at about 9.5 km/s at GO GPa, outside the ordinate range of the graph in Figure 3. Styrofoam with decreasing density, which have equivalent smaller mesostructure, yield lower shock levels. The initial shock pressure of aluminum impacting a 16 mg/ml styrofoam at 10 km/s is about 1.8 GPa, considerably below the incipient melting point of aluminum. This is encouraging and points to the need for media of ever lower density to achieve intact capture.

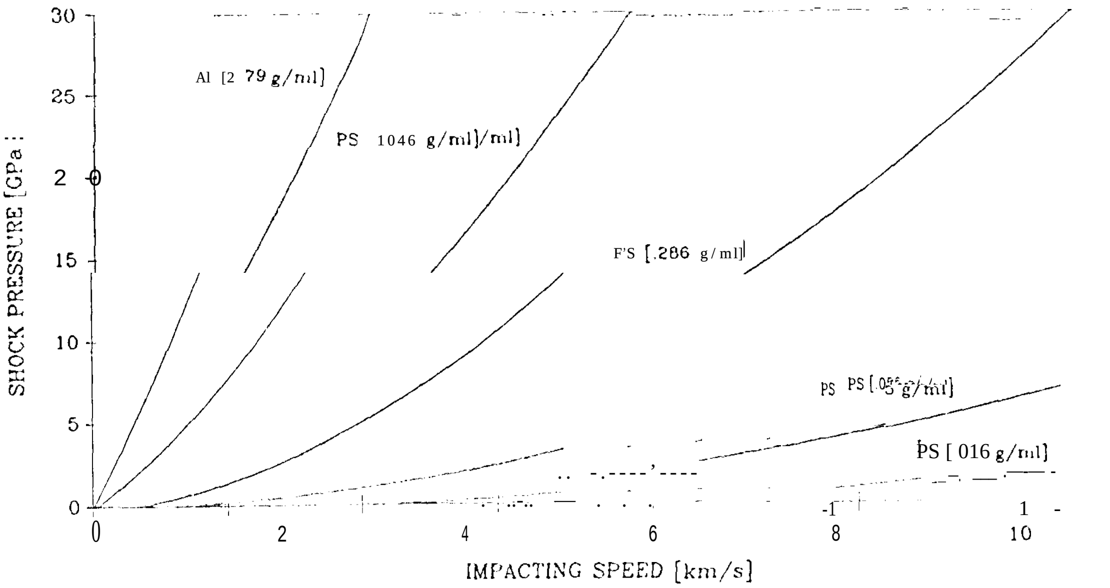

Figure 3. Shock Pressure of Aluminum impacting Polystyrene

2.2 *Intact Capture Technology*

The intact capture technique uses appropriate material to reduce the energy of hypervelocity particles gradually in order not to vaporize or melt the particles. It is even more attractive since it is accomplished passively, as illustrated in Figure 4. A passive technique does not require precision pointing, mechanisms to warm up, or devices to obtain incident speed, etc. Passive capture is simple; simplicity renders it elegant. After a decade of effort, the development of a collection technique suitable for intact capture of hypervelocity particles has been successfully demonstrated by the capture intact of 0.1 μm sized iron particle at 22 km/s [7] under laboratory simulation. Several space flights have provided definite proof of intact capture [8]. This technology will enable comet coma sample return missions or an Earth orbital cosmic dust collection mission.

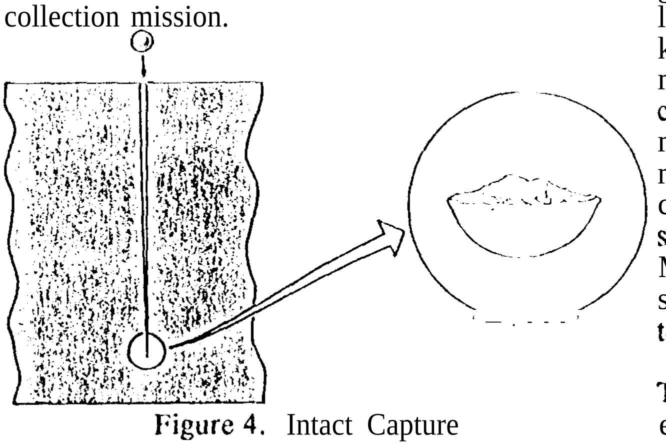
Figure 4. Intact Capture

2.3 *Laboratory Development*

In 1983, initial laboratory experiments were performed with 3.2-mm-diameter aluminum projectiles impacting expanded polystyrene foam of 18 mg/ml density at about 6 km/s using NASA Ames' vertical two-stage light-gas gun [3]. This resulted in the startling discovery that more than 75% of the original projectile mass was captured. Even more encouraging, the projectile was in one piece; there was no spallation, and the projectile looked liked the original shiny sphere, except for erosion on the front surface. It was intact! Subsequently, to generate a good database on intact capture, systematic and extensive simulation experiments were performed with the two-stage light-gas gun, plasma drag gun and electrostatic accelerator [9]. The light-gas gun simulation experiments consisted of launching projectiles at known speeds with known mass and integrity into various capture media in vacuum and at room temperature. The captured projectiles were then characterized by measuring the amounts of mass recovery, perimeter profiles, and surface erosion features. The capture media were examined for track dimensions, mass loss and surface composition. Methods of analysis included optical microscopy, scanning electron microscopy and x-ray diffractometry.

To assess the effects of projectile size, selected experiments with projectile sizes ranging from

0.1 μm to 6.35 mm were performed. To better characterize the influence of projectile material on intact capture, iron, copper, lead, glass, geological rocks, and even actual lunar sand were also used [10]. To investigate the mesostructural effects of capture media, polymer foams, films, fibers, microsphere, and high density gas were tested. Many polymer foams, including polystyrene, polyurethane, polyethylene, and polyamide, were tested with densities from 9 to 100 mg/ml. Thus far, the highest intact mass recovery in the 6 km/s range has been obtained using foams made from polystyrene with extremely fine mesostructure [11].

2.4 *Effective Capture Media*

As more hypervelocity intact capturing experiments were performed, a clear set of capture media material properties producing good intact capture results began to emerge. First, the capture media need to be extremely underdense, the bulk density considerable less than the parent material. However, we have shown that intact recovery does not follow the reduction of capture media's density indefinitely. In fact, below a threshold of low densities, the mesostructure of the capture medium dominates the effectiveness of intact capture [12,13]. That is to say, a capture medium with considerably lower bulk density produces less intact capture than one with higher bulk density, but with the desirable mesostructure. This is demonstrated in Figure 5 for various mesostructures of polystyrene foam

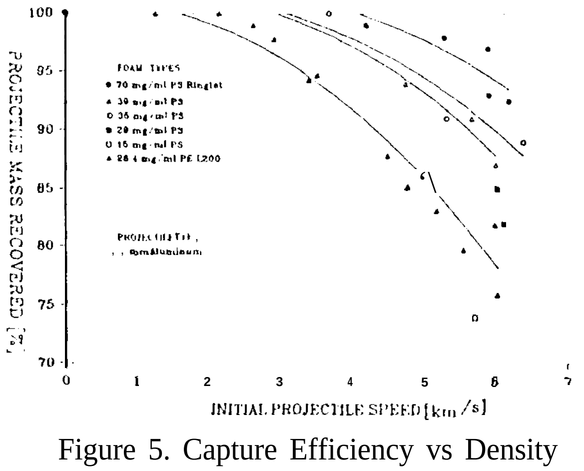

Figure 5. Capture Efficiency vs Density

Since our objective is the development of an intact capture technique for acquiring cosmic dust in the 0.1 μm to 100 μm range, the ability to locate and remove captured particles is nearly as important as their intact capture itself. Not finding a captured particle in an opaque capture medium can be equivalent to no capture at all. Locating micrometer sized particles on a surface is difficult enough for a large collection surface area; finding such a particle in an opaque solid can be a monumental task. Polystyrene foam is most effective in intact capture, but it is opaque. Since the ultimate objective is to extract and analyze the capture of μm sized cosmic particles, the effectiveness of an intact capture medium must be determined not only by the efficiency of intact capture but also on the extractability of small particles.

3. Ncw Capture Media

The search for a better intact capture medium focused on low density, fine mesostructure and transparent media. From earl y 1986, silica foam, metallic smoke, water glass, and other exotic laboratory novelties were explored as possible capture media. Not until early January 1987, during a visit with Joe Williams, our super performer polystyrene foam fabricator at the Los Alamos National Laboratory, was silica aerogel casually shown to be one of the many microcellular foam materials they had made. One sight of that small piece of aerogel generated such tremendous hope of actually having found an even better capture medium. The bulk density was high, in the range of 100s mg/ml. The mesostructure was purported to be in the range of tens of angstroms, and the sample was transparent! Unfortunately, Williams ceased making aerogel and no sample was available for our evaluation tests. The only commercially available silica aerogel was made by Airglass AR, but it is in Sweden. On contacting Sten Henning of Airglass, it was found that 6 cm x 6 cm x 3 cm blocks in the range of 200 mg/ml and higher could be purchased.

Then, having learned that Larry Hrubesh of Lawrence Livermore National Laboratory (LLNL) was making silica aerogel, and not wanting to waste any time, contacts were made, and aerogel samples for evaluation were sought. At the time, performance of one evaluation test required at least a 5 cm x 5 cm x 30 cm block of capture material. Fortunately, 120 mg/ml and 350 mg/ml aerogel in 2.5 cm x 6.4 cm x 12.7 cm blocks were promised. By early April 1988, the samples were received and the first hypervelocity intact capture tests were performed immediately at the NASA Ames Vertical Gun Facility. The results showed that projectiles were severely flattened but retained most of their mass. Although aerogel was translucent with a milky shade, nevertheless a 1.6 mm projectile was clear] y visible [I 4]. Convinced that the poor intact recovery was due to high density, lower density aerogel was requested. Sten Henning visited the Jet Propulsion Laboratory (JPL) in May 1987 and brought with him then the world's only block of 80 mg/ml aerogel; unfortunate] y, he would not leave any samples. We had to depend on LLNL for lower density aerogel. By February 1988, 50 mg/ml aerogel was successfully produced at LLNL and we tested it on March 2 with greatly improved intact capture capability. This proved the viability of aerogel as an intact capture medium.

Thus far, aerogel samples were provided to us entirely through the generosity of Larry Hrubesh, and as their schedule allowed at LLNL, since we provided no funding for the effort. Not content with the 50 mg/ml density, we brazenly continued to urge on their search for methods to produce even lower density aerogel. At the same time, LLNL continued to improve their low density aerogel with increasing clarity, fewer defects and even higher yields.

3.1 *Capturing Efficiency*

Having silica aerogel samples in a workable density, systematic evaluation of aerogel against the better performance of organic underdense media were carried out [11]. The best underdense medium performer is polystyrene emulsion foam with ringlet mesostructures. This off white colored foam has a loose powdery feel when handled and is opaque. Its bulk density ranges from 60 to 100 mg/ml with ring-like mesostructure about 10 μm in size. The other good performer is phase separated polyacrylonitrile underdense foam with a corn flake like mesostructure made in Sandia National Laboratory by James Aubert. The flakes are a few microns in size with densities on the order of 45 mg/ml. Its color is also off-white and it is opaque.

In order to make quantitative comparisons among the capture media, consistent and reproducible hypervelocity capture simulations were used. We adopted a 1.6 mm diameter polished aluminum spherical projectile as a standard with which to evaluate all prospective capture media. All experiments were performed in a vacuum of about 5 mm Hg. Intact recovery results for the three media used are shown in Figure 6. The capturing efficiencies of the three capture media are compared to our baseline capture medium, a commercially available polyethylene microcellular foam (solid line) with a bulk density of 28 mg/ml having a 100 μm polygonal cellular mesostructure. Capture efficiency or projectile mass recovery refers to the mass of the captured, intact project ile compared to its original mass. For 1.6 mm diameter aluminum projectile, polystyrene foam produced the highest mass recovery. Polyacrylonitrile foam was second highest. Aerogel at 50 mg/ml captured slightly less mass than our reference polyethylene foam.

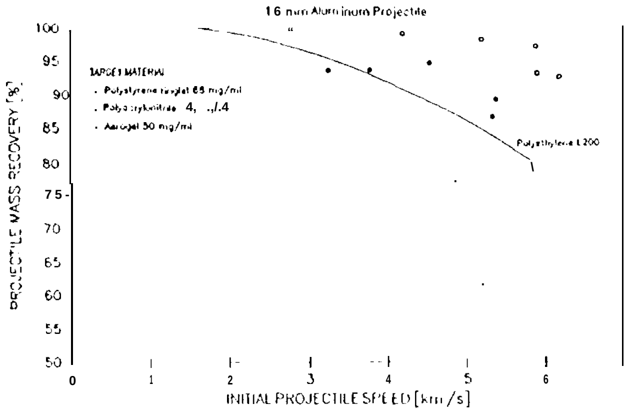

Figure 6. Capture Efficiency

3,2 *Projectile Profile*

Based upon the shape of the recovered projectiles, polyacrylonitrile demonstrated the best projectile profile preservation, with only frontal erosion and no diameter change, as shown in Figure 7. Projectiles recovered in aerogel revealed a somewhat conical frontal surface with hammered facets. Polystyrene produced the most deformed projectile, as evident in the increased diameter of the recovered projectile profile.

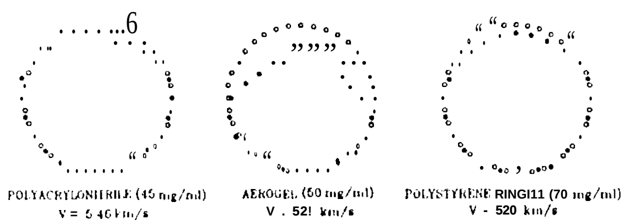

Figure 7. Recovered Projectile Profile

Subsequently, with the availability of 20 - 30 mg/ml density aerogel, the capture efficiency was improved enough to be comparable to polyethylene. However, the analyzability of aerogel more than compensated for its lower capture efficiency. In subsequent developments, aerogel offered other outstanding properties not available in organic capture media. We have now adapted aerogel as our baseline capture medium.

4. Aerogel Capture Media Development

Apparently the challenge of this new application of aerogel for the possibility of capturing cosmic dust intact intrigued LLNL so much that even without our financial support they embarked on a concerted quest to satisfy our need for ever lower density and clearer aerogel than had been achieved up to that time. A systematic characterization of our first attempt to use silica aerogel for space cosmic dust capture serves to document the level of aerogel fabrication technology at the time. In looking back, some of the 1988 challenges, when compared to what is produced today, show how much progress has been made in aerogel fabrication. However, at the time, these challenges loomed over us and pressed for solutions in order to meet a flight schedule. Some of the challenges became the research agenda of aerogel development in the intervening, years; several challenges continue to elude us even to this day.

4.1 *Density Reduction*

A few months after receiving the first samples in 1988, 50 mg/ml silica aerogel with good clarity was produced by LLNL. Sometime later, a call informed us that 30 mg/ml had been achieved. By early 1990, they had reached 10 mg/ml, 5 mg/ml; then finally, 1.9 mg/ml ! That is lighter than air! It is 0.7 mg/ml without air! Figure 8 shows the history of LLNL's aerogel density reduction quest. This was unfunded development, an amazing achievement. During this remarkable aerogel density reduction development, the first opportunity of a space flight became available to JPL. Naturally, we were to use silica aerogel along with polymer foam as a capture medium, and LLNL was asked to provide space flight aerogel. Our goal was to produce 56 flight qualified 4.4 cm x 2.4 cm x 1.6 cm aerogel blocks. Then, token funding was provided by JPL to LLNL in June of 1988 for this work. Subsequently, other funding sources were added to further develop aerogel for cosmic dust collection at LLNL. The ability to fabricate very low density aerogel was predicated on their development of the two-step approach [15] which offered unique mesostructure, as well as a convenient technique for producing very low density aerogels.

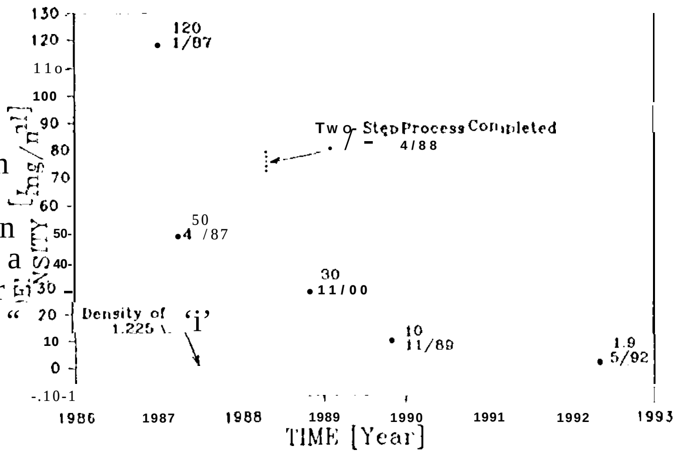

Figure 8. SiO_2 Aerogel Density Reduction

4.2 *Mold*

Another challenge is that of making cost effective molds for a quality aerogel piece. The initial molds used at LLNL were made of glass. It is was costly to shape glass to the desired dimensions, and worst of all, aerogel sticks to the mold, which can cause severe cracks in the aerogel. Aluminum foil molds are easy to fashion but have bad oxidation marks, and some mold actually turned into a pile of powder during the extraction. In order to meet our flight schedule, JPL initiated a series of mold developments by machining to the final desired dimensions while allowing for shrinkage with brass, stainless steel, aluminum (then anodized or PFA coated), and PFA teflon. Machining individual molds can be very costly, especially in the case of stainless. The result, anodized and PFA coated molds blistered, while teflon molds distorted after use. Aerogel did not stick to a pure teflon mold; unfortunately, most of the mold was badly distorted after a single extraction. Material and labor costs amounted to more than fifty dollars per mold. Figure 9 shows some of the development molds.

4.3 *Shrinkage*

The consistency and accuracy of the finished dimensions of each piece of flight aerogel are important, since all the blocks have to fit exactly into a designed fixture and are subjected to extensive thermal, vibrational and vacuum tests. Typical LLNL rule of thumb was about a 15% dimensional shrinkage. As it turned out, this was not well controlled. Of the more than two hundred blocks LLNL made for JPL, the shrinkage actually varied by as much as a factor of two. A propensity for higher shrinkage in the smaller dimensions was observed, The volumetric shrinkage was as much as a factor of 7.6. After quality control inspections, the finally acceptance ratio was less than 25 %. Figure 9 gives an indication of the shrinkage as well.

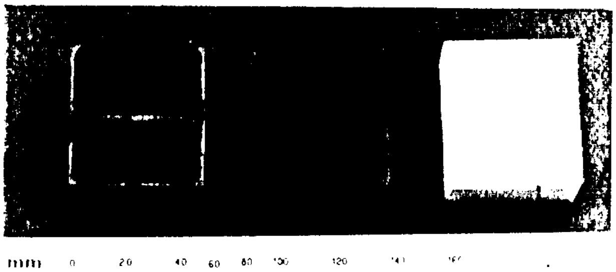

Figure 9. Teflon Coated & Teflon Molds

4.4 *Warpage*

Another facet of dimensional shrinkage is warpage, differential distortion in a given dimension or the departure from a straight line into a curve. The visual effect of warpage is bent and skewed blocks, not unlike corn chip snacks. This effect has been observed in all of the blocks in all three dimensions, but in varying degree. Dimensional warpage can be as much as 10% and the warpage preference is in the smaller dimensions. The curvature effect can result in as much as a 25% departure from a straight line, and tends to be pronounced in the longer dimensions,

4.5 *Crackage*

There did not seem to be a systematic crack pattern or the same degree of trackage in the aerogel blocks. Some aerogel blocks became two large blocks, and some even appeared to turn into piles of sand. Some cracks did not sever the aerogel, but were visible within the block. These cracks are unlike a broken window glass where cracks propagate in straight lines radially emanating from the impact point, but rather appeared random in direction, emanating from within the aerogel block. Some cracks sever the block when handled, while other cracks seem to be very stable, even when subjected to some stress by pressing.

4.6 *Discoloration*

An obvious indication of contamination of aerogel is its discoloration, or color variation within the same block or among different blocks. The prevalent type of discoloration was a colored box suspended within the aerogel block. The internal box was faint gray, blue, pink or milky white with a clear thin outer wall surrounding the suspended color block. On some, the entire block was uniformly gray, blue, yellow or pink. Another type of discoloration appeared to be a uniform translucent block of aerogel with all its edges darkened. The prevalent discoloration was milky in color and semiopaque. Only clear aerogel blocks were accepted for flight.

4.7 *Debris*

Discoloration is one form of contamination but that form of contamination uniformly permeated the aerogel block. The size of contaminants causing the discoloration were very fine. When large foreign debris is embedded within aerogel, the concerns for cosmic dust collection are twofold: the debris can be confused with cosmic dust particles, and it can cause cross contamination of captured cosmic dust particles. Under the microscope, we have seen various type of debris found under ordinary laboratory, conditions, specks of dust or fibers. We even found a portion of a house fly, we believe, embedded in one aerogel block. Of course, this could provide evidence of extraterrestrial life - a cosmic fly!

Actually, many of the initial aerogel blocks from LLNL possessed some or all of the above characteristics. In looking at them now, they seem rather artistic, rendering a rainbow effect expressed in various colors, sizes and shapes. However, we had difficulty satisfying both flight quality control and strict scheduling requirements. Fortunately, for other reasons, that first flight hardware was not flown for we would not have met the schedule. Subsequently, for the first actual space flight opportunity in 1992, we were forced to fabricate the silica aerogel cells in-house. We made significant progress in overcoming most of above challenges and now have successfully produced flight qualified silica aerogel for space flights.

5. **Space Intact** Capture with **Aerogel**

Since no amount of laboratory simulation can substitute for capturing actual cosmic dust in space, a concerted effort was made to gain access to space. This turned out to be a decade long pursuit, final] y realized in 1992. Every year since, we have had the opportunity of space flight.

5.1 *Shuttle GAS SRE*

Five thermal insulated end covers for the Shuttle Get Away Special (GAS) payload canisters were modified to hold our Sample Return Experiment (SRE) of capture cells [16]. These end covers were placed on top of the GAS payload canisters. Each SRE is 57.6 cm in outer diameter, and contains twenty-one 10 cm x 10 *cm x* 1 cm silicon aerogel capture cells. The JPL silica aerogel capture cells had densities of the order 20 mg/ml. Each of the aerogel capture cells was cast individually in the desired dimensions. To minimize concerns for launch vibration damage, each capture cell was initially edge-wrapped with a thin layer of space approved polyamide foam for a snug fit. Subsequently, this wrapping was found unnecessary. Each GAS SRE provides a net total of O. 165 m^2 capture surface.

The GAS bridge is mounted in the aft of the Shuttle payload bay. Figure 10 shows our three SREs mounted on the GAS bridge before integration in the Space Shuttle payload bay. The top of the capture surface was at about mid-height of the Shuttle payload bay. As the Shuttle payload bay door opened, SRE's field of view was limited mostly by the Shuttle's tail giving us about a 750 acceptance angle. The field of view from

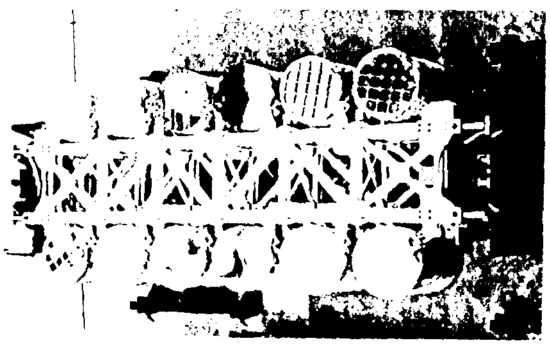

Figure 10. Shuttle GAS SRE

the starboard and port sides was essentially a full 180°. STS-47 was an extended 9 day mission running from September 11 through September 19, 1992. The cruising altitude was 300-304 km at a 28.50 inclination. The Shuttle's tail was pointed at Earth while its right wing pointed in the direction of the velocity vector; consequently, the face of the SRE was orientated normal to the ram direction, facing space in the plane perpendicular to the line from the Shuttle to Earth. This total 'space' exposure time was estimated to be approximate y 170 hours.

5.2 *Shuttle Spacehab SRE*

Spacehab is a commercial endeavor to facilitate the entry to space flight for commercial businesses. It just so happened that the Spacehab module had a flat roof. An excellent opportunity was, thus, made available to attach our SRE on top of the Spacehab module. On STS-60, two large modules with 80 silica aerogel capture cells on each panel were flown. The silica aerogel capture cells were our standard 10 cm x 10 cm x 1 cm cell at 20 mg/ml density. This was nearly a total of 1.6 m^2 of aerogel. Figure 11 shows the inflight photograph of our SRE with a view of Earth in the background.

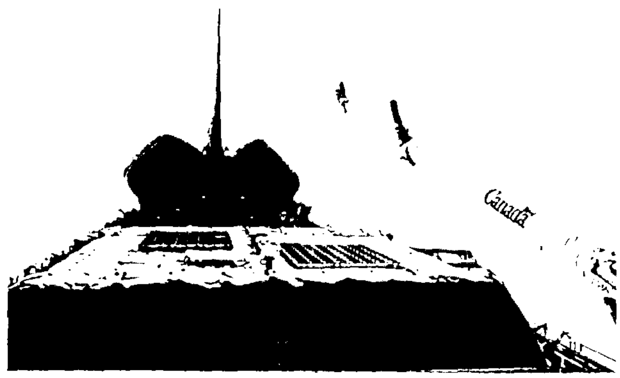

Figure 11. Spacehab SRE

5.3 *Results*

All aerogel cells were returned without any apparent damage. Upon initial examination, there were at least four large hypervelocity particles captured in three of the cells from STS-47 GAS SRE and more than two dozen from STS-60 Spacehab SRE. Ample evidence of the notorious Shuttle payload bay contamination has also been captured intact on our aerogel cells. Initial optical examination of the captured hypervelocity particles has been carried out. Particles will then be. extracted, followed by their chemical and structural anal yses. Figures 12a shows two captured particles with typical textbook carrot tracks. The intact particles are lodged at the end of the capture track. In fact, the capture track is essential in locating the particle. Locating micron sized particles without any demarcations would be very difficult indeed, even if the capture medium is transparent. The track length is typically 100 to 200 times the diameter of the captured particle and serves as an excellent pointer. Figure 12b is an enlarged view of the particles at the end of the tracks in Figure 12a. The next step in analysis would be to remove the particle and subject it to scanning electron microscop y and, when appropriate, microtoned for transmission electron microscopy. Other analytical techniques are used for specific studies.

Figure 12a&b. Intact Captured Particle

6. Unique Features of Aerogel in Space

The initial motivation for using silica aerogel was to find a transparent capture medium that possesses low density and fine mesostructure. Certainly, silica aerogel fulfilled these requirements [17]. Even more so, with increased space flight experience, we have learned of a host of other exceptional properties of silica aerogel equally as important as the initial motivation in introducing aerogel. A recounting of these unique features of silica aerogel for space flight applications will not only further support the use of aerogel as a cosmic dust collection medium, but also suggest other new applications. Special and careful handling, however, is a necessary precaution when aerogel is used.

6.1 *Wide Dynamic Range*

Cosmic dust's size range of interest encompasses at least four orders of magnitude, 0.1 μm to a few mm. Generally, the dynamic range of the detector needs to follow the wide ranges of variation in the detecting phenomenon. The applicable aerogel density for cosmic dust collection spans from 100 mg/ml to 1 mg/ml, a respectable three orders of magnitude in dynamic range. This wide density span of silica aerogel is comparable to the wide particle size range encounter in cosmic dust collection. Lower densities would be more suitable for smaller dust particles; no solid material has lower density than silica aerogel!

6.2 *Volatile Absorbance*

Hypervelocity capture of cosmic dust is a highly energetic, catastrophic event. At the time of capture, volatiles entrapped within the dust particle will likely undergo a phase change. With a high surface area, the volatiles will likely recondense on these large contact surfaces and, in effect, be adsorbed. Since silica aerogel has the highest surface area of all solid materials, the effectiveness of volatile adsorption in aerogel is most favorable. This feature actually enables a single capture medium to perform a dual science function: intact capture of cosmic dust and efficient physical or chemical capture of volatiles.

6.3 *Momentum Transfer*

Intact capture experiments in polymer foams showed melted polymer sticking to the frontal surface of the intact recovered projectile at lower initial projectile speeds. The effect of melted capture medium sticking to the projectile reduces its speed and protects the projectile. Silica aerogel even at higher hypervelocities exhibits this sticking effect. The melted glass wrapping around the frontal portion of the projectiles seemed to be much more pronounced in silica aerogel, as shown in Figure 13. This effect increases intact capture. This beneficial feature is especially significant for capturing tiny and fragile dust particles. This sticking effect may be helped further by preventing the breakage of fluffy particles.

6.4 *Cleanliness*

The prime objective in cosmic dust collection is to learn all about the captured material's chemical and structural compositions. Therefore, it is important that the capture medium be extremely

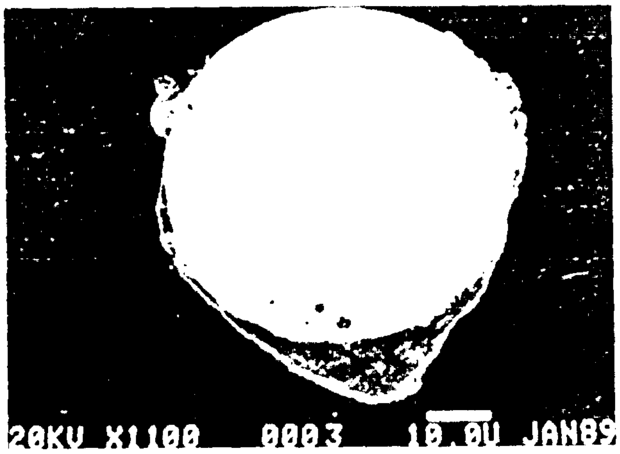

Figure 13. Aerogel Wrapped Particle

pure and clean in order to minimize source uncertainty and cross contamination. The best commercially available clean material would be silicon wafers used in the production of semiconductors. The high end product value of semiconductors can justify such an enormous investment for ultra clean facilities. The fabrication process of semiconductor grade silicon would likely produce one of the cleanest of commercial materials available. We were pleasantly surprised to learn that the silica aerogel we produced is of comparable cleanliness to semiconductor silicon, as shown in Figures 14a through 14d. This is understandable, actually, since the critical point extraction process is inherently a thermal cleaning process.

6.5 *Launch Load Robustness*

All space flight hardware must first survive a rough rocket ride to escape the Earth's gravity. For sample return, there are the disruptive atmospheric reentry and ground landing. All flight hardware destined for space must be flight qualified by vigorous vibration testing. We first thought the greatest impediment to aerogel flight qualification would be vibration, and we were. concerned about the 'fragile' aerogel not surviving the shake table. Shaking a household glass window will ensure its breakage but not so with a wad of cotton. Such is the case with aerogel. Even the microcracks in aerogel did not propagate on the shake table. Aerogel is very robust for rocket launch!

6.6 *Thermal Cycling Robustness*

In space, without the amelioration of our atmosphere, the temperature of a metallic surface can be 200° C when facing the Sun and instantly drop to -100° C when turned away from the Sun, This thermal cycling can cause havoc for much earth-bound equipment. This is the reason that most space vehicles are either very dark for absorption, or very bright for reflection. Inherently, aerogel is a good insulator. Thermal cycling does not adverse] y affect aerogel. Due to the fine mesostructure, aerogel has high emissivity and, as a result, does not trap heat.

6.7 *Radiation Robustness*

The Earth's atmosphere serves many functions for sustaining life on the Earth's surface. One, not commonly recognized function is shielding us against much harmful space radiation, such as ultra violet (UV) radiation. Silica aerogel, being inorganic, is impervious to radiation, unlike organic polymer foams, where radiation will harden and damage the structure. In fact, embrittled polystyrene turns into powder under UV.

6.8 *Ionic Robustness*

In recent years, frequent near Earth orbital flights taught us that although Mylar and Teflon are rather strong organic materials for Earth surface applications, they seem to evaporate in space. Experience has indicated that for one, atomic oxygen alone can remove ~1 μm/day [18,19]. For underdense foam, the removal rate would be considerably higher due to the decreased density. Silica aerogel is inorganic and not affected by ionic erosion. In fact, oxides of silicon are used as a coating for organic polymer material to protect it against ionic erosion.

6.9 *No Mass Constraints*

Transporting mass to space can be achieved only at a high premium; the transportation system to payload mass mass ratio is around 10,000. Thus, the lighter the space hardware the better it is. Aerogel collectors have the distinct advantage of having very low mass. In fact, the fixtures that carry the aerogel has a mass density at least two order of magnitude higher. Even for very large collector surface area, mass constraints will never arise from aerogel.

6.10 *Handling Caution*

All delicate space instrumentation has to be

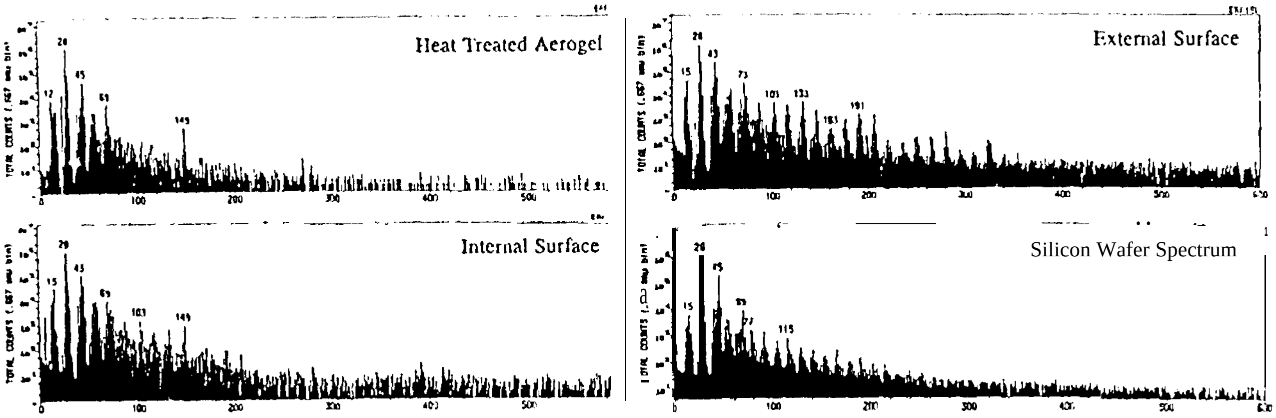

Figure 14a-c. Cleanliness of JPL SiO_2 Aerogel

handled with care. However, in the case of aerogel, added caution is required. Being transparent, very good lighting must be provided in the work area to prevent accidental damage; we have damaged many aerogel capture cells, ibis manner. 'I'he work environment cannot bc drafty. A slight air movement may cause lift off of an aerogel capture cell. Moreover, we have not found a method to clean the surface debris without doing some damage to the aerogel surface. Thus, the work environment needs to be clean and debris free. Then too, static sticking can turn aerogel into fly paper for room particulate. We know that volatiles condense on aerogel very effective y; thus, the work environment must have controlled volatiles release, e.g., cleaning solvents.

For our Shuttle flights, we have successfully produced fully flight-qualified silica aerogel for use in the space environment. In fact, silica aerogel is so unique that it is the only intact capture medium that can be fully flight qualified without various additional remedial actions being necessary.

7. Conclusion

Silica aerogel, besides being low in density, fine in mesostructure and transparent, has many features that are well suited as a passive capture medium for cosmic dust collection. Aerogel as a class of material, with silica being one formulation, will likely be the capture media type used for cosmic dust collection for a long time to come. Currently, the capture efficiency of silica aerogel fal Is below the best of polymer foams. One of our goal is to improve the capture efficiency of aerogel even further.

Acknowledgements

Working with Larry Hrubesh on the development of silica aerogel has been most rewarding and productive, and we are grateful for his teaching us how to make aerogel. We are indebted to Joel Williams for the inspiration he provided by showing us his aerogel as well as for his production of high performance polystyrene foam, We would like to thank James Aubert and Rick Pekala for providing polyacrylonitrile foams and organic aerogel samples, respectively, for our laboratory simulations. The productive research collaboration of the last decade from Arden Albee and Donald Brownlee, members of the Intact Capture Research Team, is gratefully acknowledge. Suggestions and editorial assistance on this paper from David Griffiths is much appreciated. Our thanks also go to the NASA Ames's Vertical Gun Range crew for their able and enthusiastic support. Finally, this work was carried out in part by the Jet Propulsion Laboratory, California Institute of Technology, under a NASA contract.

References

[1] Tsou, P., D. E. Brownlee & A. L. Albee, Int. Conf. Comet Exp. Vol II. (1983) 215.

[2] SSEC, NASA (19s3)]49.

[3] Tsou, P., D. E. Brownlee & A. L. Albee, LPSC 15, (1984) 866.

[4] Tsou, P., D. E. Brownlee & A. L. Albee, LPSC 19, (1988) 1205.

[5] Marsh S. P., Univ. Calif. Press (1980).

[6] Tsou, P., Jnt. J. Impact Engng Vol. 10 (1990) 615.

[7] Tsou, P., & A. L. Albee, LPSC 23, (1992).
[8] Tsou, P., D. E. Brownlee & A. L. Albee, LPSC 24, (1993).
[9] Tsou, P., W. Kromydas & A. L.. Albee, LPI No. 88-01 (1988) 62.
[10] Tsou, P., D. E. Brownlee & A. L. Albee, LPSC 22, (1991).
[11] Tsou, P., D. E. Brownlee & A. L. Albee, LPSC 20, (1989).
[12] Tsou, P., D. J. Griffiths, D. J. Buettner, Top. Conf. on Shock Comp. of Cond. Matter (1991).
[13] Griffiths, D. J., D. J. Buettner & P. Tsou, JAP January 1992.
[14] Tsou, P., D. E. Brownlee & A. L. Albee, LPSC 21, (1 990).
[15] Hrubesh, L., T. M. Tillotson & J. F. Poco, UCRL 102518 (1990),
[16] Tsou, P., D. E. Brownlee & A. L. Albee, LPI 93- (1993).
[17] Tsou, P., D. J. Griffiths & A. L.. Albee, LPI 93- (1993).
[18] NASA Conf. Pub. 3194 (1992).